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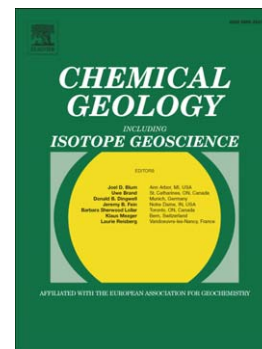
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A general viscosity model of Campi Flegrei (Italy) melts

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Abstract

Viscosities of shoshonitic and latitic melts, relevant to the Campi Flegrei caldera magmas, have been experimentally determined at atmospheric pressure and 0.5 GPa, temperatures between 840 K and 1870 K, and H₂O contents from 0.02 to 3.30 wt%.

The concentric cylinder technique was employed at atmospheric pressure to determine viscosity of nominally anhydrous melts in the viscosity range of $10^{1.5}$ - 10^3 Pa·s. The micropenetration technique was used to determine the viscosity of hydrous and anhydrous melts at atmospheric pressure in the high viscosity range (10^{10} Pa·s). Falling sphere experiments were performed at 0.5 GPa in the low viscosity range (from $10^{0.35}$ to $10^{2.79}$ Pa·s) in order to obtain viscosity data of anhydrous and hydrous melts. The combination of data obtained from the three different techniques adopted permits a general description of viscosity as a function of temperature and water content using the following modified VFT equation:

$$\log \eta = -a + \frac{b}{(T - c)} + \frac{d}{(T - e)} \cdot \exp\left(g \cdot \frac{w}{T}\right)$$

where η is the viscosity in Pa·s, T the temperature in K, w the H₂O content in wt%, and a , b , c , d , e , g are the VFT parameters. This model reproduces the experimental data (95 measurements) with a 1σ standard deviation of 0.19 and 0.22 log units for shoshonite and latite, respectively. The proposed model has been applied also to a more evolved composition (trachyte) from the same area in order to create a general model applicable to the whole compositional range of Campi Flegrei products.

Moreover, speed data have been used to constrain the ascent velocity of latitic, shoshonitic, and trachytic melts within dikes. Using petrological data and volcanological information (geometrical parameters of the eruptive fissure and depth of magma storage), we estimate a time scale for the ascent of melt from 9 km to 4 km depth (where deep and shallow reservoirs, respectively, are located) in the order of few minutes. Such a rapid ascent should be taken into account for the hazard assessment in the Campi Flegrei area.

1. Introduction

Viscosity is a key factor governing both intrusive and volcanic processes. The most important parameters affecting the viscosity of silicate melts are melt composition and temperature (Bottinga and Weill, 1972; Shaw, 1972). Pressure has only a minor effect at crustal depths whereas crystals and bubbles have a dramatic influence (Kushiro et al., 1976; Pal, 2002; Behrens and Schulze, 2003; Vetere et al., 2010). Among compositional parameters, the volatile content (mainly H₂O) is critical because it affects the rheological behaviour of melts and thus eruptive styles. Consequently, an appropriate knowledge of magma viscosity as a function of dissolved volatiles is mandatory to obtain reliable models of volcanic processes (i.e., magma ascent, fragmentation, and dispersion) which in turn required to predict realistic volcanic scenarios and forecast volcanic hazards (Misiti et al., 2006; Papale, 2001).

The Campi Flegrei volcanic complex, located in the urbanised Neapolitan area (South Italy), was chosen as case study because it is an active volcanic field that experienced predominantly strongly explosive volcanic activity. The city of Pozzuoli lies close to the Solfatara crater while Naples, with 1.5 million inhabitants, is nearby, between Campi Flegrei and Vesuvius. The volcanic risk in this area is significant because of the large population and this is a compelling reason to better understand the evolution of the Campi Flegrei complex and the mechanisms leading to explosive eruptions.

Viscosity of two Campi Flegrei compositions, representative of parental magmas, has been investigated in the temperature range 840 - 1870 K and H₂O contents in the melt ranging from 0.01 (nominally anhydrous) to 3.30 wt%. The combination of viscosity data obtained in a wide temperature and water content range, permits a general description of the viscosity as a function of temperature and water content using a modified Tamman-Vogel-Fulcher equation.

Using this equation we can calculate viscosity values for the two studied compositions under the conditions inferred for Campi Flegrei magma chamber. One important application of these data is the estimate of the flow regime and the magma rising velocity from deep to shallow reservoirs.

2. Geological and volcanological setting

The Campi Flegrei (**Fig. 1**) is a restless, nested caldera structure resulting from two main collapses related to the two most powerful eruptions of the volcanic system (Orsi et al., 1996 and reference therein): the Campanian Ignimbrite (37 ka, Deino et al., 1992; Armienti et al., 1983; Rosi and Sbrana, 1987; Rosi et al., 1983, 1996; Barberi et al., 1991; Fisher et al., 1993; Civetta et al., 1997) and the Neapolitan Yellow Tuff (12 ka, Alessio et al., 1971; Orsi and Scarpati, 1989; Orsi et al., 1992, 1995, 1996; Wohletz et al., 1995).

The two investigated compositions are a shoshonite from Minopoli and a latite from Fondo Riccio. The latter was an explosive strombolian eruption occurred near the centre of the Campi Flegrei caldera (9.5 ka), whereas the shoshonite belongs to an explosive hydromagmatic eruption that occurred along the regional fault system in the northern portion of the same caldera (9.7 ka). Both are peculiar in the Campi Flegrei activity because their products present the less evolved compositions compared to those erupted from other eruptions in the area. For detailed geological, volcanological and chemical descriptions of these eruptions see Di Vito et al. (1999), D'Antonio et al. (1999) and Pappalardo et al., (2002).

In melt inclusions from both eruptions detected H₂O and CO₂ contents range from 0.2 to 2.84 wt% and from 172 to 1100 ppm, respectively (Mangiacapra et al., 2008). For both investigated eruptions two depths of melt inclusions eruptions were estimated at 4 and 9 km

(Mangiacapra et al., 2008). In addition, these results closely agree with the geophysical analysis of Zollo et al. (2008).

3. Analytical and Experimental Methods

3.1 Starting material

The starting material was produced from two natural scoria samples belonging to Minopoli and Fondo Riccio eruption deposits, respectively (Di Vito et al., 1999). These samples were selected for this study and for previous ones (Di Matteo et al., 2007; Cannatelli et al., 2007) because they represent the less evolved magmas among Campi Flegrei products: i.e., shoshonite (Minopoli) and latites (Fondo Riccio) (D'Antonio et al., 1999).

Anhydrous starting materials for micropenetration and concentric cylinder viscosity measurements were prepared at Department of Earth and Environmental Sciences, Ludwig Maximilians Universität München (Germany). About 100 g of both samples were melted and homogenised in a Pt₈₀Rh₂₀ crucible placed in a MoSi₂ box furnace at 1873 K for about 1 hour at atmospheric pressure. The obtained anhydrous melts was then quenched, by partially dipping the crucible in water, in order to obtain crystal and bubble free glasses. An aliquot of the anhydrous quenched glass was crushed and ground in an agate mortar and the glass powder was loaded in platinum capsules (3 mm in diameter and 20 mm in length) with a known amount of doubly-distilled water (up to 3 wt %). Hydrous glasses were, thus, synthesized in an internally heated pressure vessel for 24 hours at 150 MPa and 1473 K; pressure and temperature have been chosen to have water under-saturated samples. Runs were isobarically quenched to avoid crystallization.

For low-temperature micropenetration measurements, cylinders of anhydrous and hydrous glasses were sawn into 3 mm long pieces. The disks were then polished on both sides and stored in a desiccator until used in the experiments.

Starting material for falling sphere experiments was prepared at the Institute of Mineralogy, Leibniz University Hannover (Germany). Anhydrous samples were prepared by dehydrating natural sample rock powders in a Pt crucible in air at 1673 K for 1 hour. Glasses with various H₂O content were then synthesised in an internally heated pressure vessel at 300 MPa, 1523 K (24 h duration) in sealed AuPd capsules (40 mm long, 6.0 mm inner diameter) containing the powdered natural sample and the desired amount of distilled water (from 2.3 up to 3.3 wt%). Quench was isobaric with control of pressure to within 25 bar of the nominal pressure.

Composition of starting materials (Table 1) was determined by electron microprobe analyses (JEOL JXA 8200) at the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Rome (Italy). Analysis conditions were: probe diameter of 5 μ m, accelerating voltage of 15 kV, and beam current of 6 nA.

3.2 Pre- and post-experimental water determination

Bulk water contents of glasses before and after viscosity measurements were determined by Karl-Fischer titration (KFT) and Fourier Transform Infrared (FTIR) spectroscopy at the Department of Mineralogy, Leibniz University Hannover. Results are reported in Table 1. The precision of the KFT data is within ± 0.10 wt% H₂O. FTIR measurements followed the method described in Behrens et al. (1996). The peak heights of the near-infrared (NIR) absorption bands at 4500 cm⁻¹ (combination mode of OH groups) and 5200 cm⁻¹ (combination mode of H₂O molecules) were used to analyze the water content of the glass after experiments. Absorption spectra of doubly polished glass slabs with thickness of 0.13–0.15 mm were collected using an IR microscope (Bruker IRscope II) connected to a FTIR spectrometer (Bruker IFS88). In the near-infrared (NIR), the spectra were measured using a tungsten light source, a CaF₂ beamsplitter and a narrow range MCT

detector. Typically 50–100 scans were accumulated for each spectrum with a spectral resolution of 4 cm^{-1} . Simple linear baselines were fitted to both NIR peaks (TT baseline according to Ohlhorst et al., 2001). The water content of the nominally dry starting glass was determined by measuring the peak height of the mid-infrared (MIR) absorption band at 3550 cm^{-1} after subtracting a linear baseline. A bulk spectrum was collected in the main chamber of the FTIR spectrometer using a polished glass section that was placed on a hole aperture 2 mm in diameter. Measurement conditions were: global light source, KBr beam splitter, DTGS detector, 2 cm^{-1} spectral resolution, 100 accumulated scans. Concentrations of hydrous species and total water were calculated from peak height of absorption bands using the Lambert–Beer law (e.g., Stolper, 1982). For the calculation, the relationship between density and water content, the molar absorption coefficients of the absorption bands, and the sample thickness are needed. Densities of hydrous glasses were calculated using Ochs and Lange (1999) equation; molar absorption coefficients used are 0.93 , 0.81 , and $60\text{ L}\cdot\text{mol}^{-1}\cdot\text{cm}^{-1}$ for the 5200 , 4500 , and 3550 cm^{-1} bands, respectively, after Di Matteo et al. (2006); sample thickness has been determined with a precision of $\pm 2\text{ }\mu\text{m}$ by using a Mitutoyo micrometer.

3.3. Viscosity measurements

3.3.1. Concentric cylinder technique.

High-temperature shear viscosities were measured at 1 atm in the temperature range 1400–1870 K using a Brookfield DVIII+ concentric cylinder. The concentric cylinder apparatus allows to determine viscosities of anhydrous melts in the range 10^{-1} – $10^5\text{ Pa}\cdot\text{s}$ with an accuracy of $\pm 0.05\cdot\log_{10}\text{ Pa}\cdot\text{s}$. The starting glass is loaded in a cylindrical $\text{Pt}_{80}\text{Rh}_{20}$ crucible (5.1 cm height, 2.56 cm inner diameter and 0.1 cm wall thickness). The viscometer head drives a spindle at a range of constant angular velocities (0.5–100 rpm) and digitally records the torque exerted on the spindle by the sample. The spindles are made from the same

material as the crucible, vary in length and diameter, and have a cylindrical cross section with 45° conical ends to reduce friction effects. The sample is heated in a Deltech Inc. furnace with six MoSi₂ heating elements. The crucible is loaded into the furnace from the base (Dingwell, 1986; Dingwell and Virgo, 1988 and Dingwell, 1989). The stirring apparatus is coupled to the spindle through a hinged connection. The spindle and the head were calibrated with a Soda–Boro–Silica glass NBS No. 710 whose viscosity as a function of temperature is well known. Samples are melted and stirred in the Pt₈₀Rh₂₀ crucible for at least 12 hours, but often up to 4 days until optical inspection of the stirring spindle indicated that melts were crystal- and bubble-free. At this point the torque value of the material is determined using a torque transducer on the stirring device. Then viscosity is measured decreasing temperature of 25 K/min. Once the required steps have been completed, the temperature is increased to the initial value to check if any drift of the torque values have occurred, due to volatilisation or instrument drift. Finally, after the high temperature viscometry, all the re-melted specimens are removed from the furnace and quenched by pouring material on an iron plate, in order to avoid crystallization.

3.3.2. Micropenetration technique.

Low-temperature viscosities of anhydrous and hydrous quenched melts were determined at 1 atm in the temperature range 840-1045 K by micropenetration viscometry as described in Brückner and Demharter (1975), Douglas et al. (1965), and Dingwell et al. (1996). This technique allows determining viscosity in the range $10^{8.5}$ to 10^{12} Pa s with an error of ± 0.06 log units (Hess et al., 1995). To calibrate the system a Standard Glass I DGG has been used (standard from the Deutsche Glasstechnische Gesellschaft). Viscosity measurements were performed in a modified vertical push-rod dilatometer (BÄHR DIL 802V) at the Maximilians Universität München (Germany). The basic principle in the technique is to measure the rate at

which an iridium hemisphere moves into a glass disk surface under a fixed load. Penetration of the Ir hemisphere into the glass sample is a function of the viscosity of the sample. The absolute viscosity was calculated by using the following equation:

$$\eta = 0.1875 P t / r^{0.5} l^{1.5} \quad (1)$$

where 0.1875 is a geometric constant, P is the applied force (in N), r is the radius (in μm) of the hemisphere, t is the penetration time (min) and l is the indentation distance radius (in μm) (Hess et al., 1995).

The applied force for all the micropenetration measurements in the present work was about 1.2 N. Double polished 3 mm thick glass disks obtained from either anhydrous or hydrous glasses (see above) were placed in a silica rod sample holder, in the push-rod dilatometer under Ar gas flow. The samples were heated up to the dwell temperature at a constant rate of 10 K/min, held at this temperature for 15 min (for hydrated samples) and 90 min (for anhydrous samples) to allow thermal equilibration and structural relaxation, then the viscosity measurement was performed over approximately 5 min. Different glass disks from the same anhydrous and hydrous glasses were used in each measurement in order to avoid effects of propagating dehydration.

3.3.3. Falling sphere method

High temperature viscosities of anhydrous and hydrous melts were determined by means of the falling sphere method (Shaw, 1963) at the HP-HT Laboratory of Experimental Volcanology and Geophysics of INGV. The method is based on the determination of the settling distance of a sphere in a liquid and requires the determination of the exact position of the sphere in a glass cylinder before and after the experiment. Details of the employed technique are described in Vetere et al. (2008) and in Misiti et al. (2009). Starting glass, ground to powder and dried in an oven at temperature of 383 K for the anhydrous sample and

at 330 K for the hydrous one, was loaded in Pt capsule (15 mm long, 3.0 mm outer diameter) along with a Pt sphere. Depending on the water content of the sample (i.e. considering that more water implies a more fluid system and consequently higher speed of the falling sphere) the radius of the spheres was varied from 50 to 215 μm . Loaded capsules were crimped and stored in an oven overnight to remove humidity and then welded. X-ray radiograph of each capsule was taken before the experiments to check the position of the sphere. Loaded capsules were inserted in a 19.1 mm NaCl-crushable alumina-pyrex (nominally anhydrous samples) or NaCl-crushable alumina-pyrophillite-pyrex (hydrous samples; Freda et al., 2001) assemblies. Experiments were carried out in a piston cylinder apparatus (intrinsic redox condition NNO+2) at 0.5 GPa and temperatures between 1423 and 1673 K. Experiments were firstly pressurized and then heated isobarically at a rate of 200 K/min up to 20 K below the set point. A rate of 40 K/min was used to reach the final temperature. The temperature was controlled by a W_{95}Re_5 - $\text{W}_{74}\text{Re}_{26}$ thermocouple and held within 3K of the experimental temperature. The thermocouple was positioned such that its junction coincides with the cylindrical axis of the furnace and the midpoint (length-wise) of the capsules, where the furnace hot-spot is estimated to be approximately 8 mm length. The run was quenched by turning off power. Quench was isobaric at a rate of about 2000 K/min. X-ray image of the capsule was made after experiment and the sinking distance of sphere was determined (within an error of ± 20 μm) by superimposing pre- and post-experiment images (Misiti et al., 2006). The velocity of Pt spheres, derived from the sphere position vs. time, was used to measure the melt viscosity by means of the Stokes law:

$$\eta = \frac{2r^2 g \Delta\rho}{9v} W \quad (2)$$

where η is the viscosity (in Pas), g is the acceleration due to gravity (9.8 m/s^2), $\Delta\rho$ is the density difference between melt and sphere (kg/m^3), r is the sphere radius

(m), v is the terminal fall velocity of the sphere (m/s) and W is a correction factor which takes into account the effects of viscosity drag exerted on the settling sphere by the capsule walls and is given by the equation (Faxen, 1923):

$$W = [1 - 2.104 (r_s/r_c) + 2.09 (r_s/r_c)^3 - 0.95 (r_s/r_c)^5] \quad (3)$$

where r_c is the inner radius of the capsule and r_s is the radius of the sphere.

Due to the short dwell times at the target temperature, sinking of the sphere before reaching the final temperature may significantly contribute to the whole falling distance. To account for movement of the sphere during heating and cooling we calculated the effective run duration $t_{\text{effective}}$ for each experiment (Vetere et al., 2006).

The activation energy of viscous flow was estimated to be 450 kJ/mol for shoshonite and 320 kJ/mol for latite at T between 1673 and 1523 K. The largest uncertainty in our experiments is the effective run duration due to the short dwell at the experimental temperature (between 300 and 1800 sec). The error in distance measurements is about 10 μm , determined mainly by the resolution of the X-ray photograph. Additional errors in viscosity determination are related to the sphere radius (1 - 5 μm), to the experimental temperature (± 10 K) and to the melt density. As an approximation we have used the density of the glass in the viscosity calculation and not that of the melt. This contributes a systematic error to the viscosity data ($\pm 3\%$, Vetere et al., 2006); however, this error is negligible compared to that originating from run duration (Table 2). Another error may be related to the shortening of the capsule during compression. However, it has been demonstrated (Misiti et al., 2006) that the shortening occurs only during compression (which is held at room temperature), so the compression does not affect the initial position of the sphere and, then, the measurements of the sinking distance (for more details see Misiti et al., 2006).

4. Results

Experimental conditions and results are reported in Tables 2 and 3. Experiments in the high viscosity regime have been performed at atmospheric pressure, temperature between 840 K and 1040 K and water contents up to 2.43 wt%; experiments in the low viscosity regime have been performed at atmospheric pressure and 0.5 MPa, temperatures between 1400 K and 1870 K and water contents up to 3.03 wt%. As for several other natural and synthetic melts (cf. Dingwell et al., 1996; Holtz et al., 1999; Whittington et al., 2000; Romano et al., 2001; Misiti et al., 2006), viscosity decreases by increasing both, temperature and water content, the decrease being more marked at low water contents (less than 0.5 wt%) and temperatures (Figs. 1 and 2). For example, by adding only 0.3 wt% of water to the latitic composition the viscosity decreases of 2 orders of magnitude for samples run at similar temperatures ($\Delta T = 20\text{K}$; $T = 950\text{--}930\text{K}$); by adding about 3 wt% water to the melt, viscosity decrease remains within 2 orders of magnitude (Table 2, Fig. 3). Interestingly, the effect of water on viscosity seems to be more efficient for the latitic composition than for the shoshonitic one; by adding about 3 wt% H_2O to the latite we observe a viscosity decrease of about 2 orders of magnitude (i.e. $T = 1423\text{ K}$) whereas, at the same experimental conditions, viscosity of the shoshonite decreases by only 1 order of magnitude (Fig. 2). Some experiments in the low viscosity regime have been duplicated at same conditions of P-T-t-sphere radius) and the results agree within the reliability of the falling sphere method (cfr. Table 3).

Notably, falling sphere experiments and concentric cylinder measurements performed at similar temperatures (1523 and 1522 K, respectively) on dry samples but at different pressures (0.5 GPa and atmospheric pressure, respectively) produced comparable viscosity

values ($\log \eta \approx 2$, Tables 2 and 3). We thus assume that the effect of pressure (between 1 atm and 0.5 GPa) was smaller than accuracy of the measurements.

4.3 The viscosity model

The viscosity data set has been used to develop an empirical model predicting viscosity as a function of melt composition and temperature. The data set consists of 58 nominally dry experiments, 30 for latite and 28 for shoshonite, and 34 hydrous experiments, 19 for latite and 15 for shoshonite.

The following equation (Vetere et al., 2007, Davì et al., 2009) based on the VFT (Vogel–Fulcher–Tamman) approach was found to best reproduce the experimental data:

$$\log \eta = -a + \frac{b}{(T - c)} + \frac{d}{(T - e)} \cdot \exp\left(g \cdot \frac{w}{T}\right) \quad (4)$$

where η is the viscosity in Pa s, w is the amount of H₂O in wt% and T is the absolute temperature, a , b , c , d , and g are the fit parameters. Note that the equation is the same for both compositions, only fit parameters, listed in table 4, change. This equation reproduces the experimental data with a standard deviation (1σ) of 0.19 log units for latite and 0.15 log units for shoshonite. In order to create one single equation to predict viscosity of the whole range of compositions erupted at Campi Flegrei we have tested Equation (4) on the data obtained for a more evolved Campi Flegrei composition (trachyte from Agnano Monte Spina eruption, Misiti et al., 2006) and calculated the related parameters (Table 4). Since Equation (4) predicts viscosity of trachytic melt with a root mean squared deviation of 0.23 log units with respect of the equation reported in Misiti et al. (2006), we can confidently use it to calculate

viscosity of more evolved trachytic compositions as well. Finally, we stress that Equation (4) can be used to predict viscosities below 10^{12} Pas.

5. Discussion

A comparison between experimental and predicted data is reported in figures 3. Based on Equation (4) the viscosity of shoshonite, latite and trachyte anhydrous melt at temperature relevant for magmatic processes (1393 K for shoshonite and latite, Mangiacapra et al., 2008 and 1218 K for trachyte, Romano et al., 2003) is $10^{3.32}$ Pas, $10^{3.90}$ Pas and $10^{6.89}$ Pas, respectively. Between the above mentioned temperatures melts with 3.0 wt% H₂O have viscosities of $10^{1.90}$, $10^{1.51}$ and $10^{3.43}$ Pas, respectively.

5.1 Comparison with previous models

Figures 3a-i show viscosity values for shoshonitic, latitic, and trachytic melts determined in this study and in Misiti et al. (2006) vs values predicted by Equation 4 (this study) and general empirical equations proposed in previous studies (Giordano et al., 2008; Hui and Zhang, 2007). In general, we notice that previous models (some are general models designed to predict viscosities as a function of melt composition and temperature whereas some others are specific models calibrated for a single composition) diverge from experimentally determined values. In particular, such a divergence is more pronounced for shoshonitic and trachytic compositions when using the Hui and Zhang (2007) model (Figs. 3b and 3i). The comparison with Giordano et al. (2008) and Hui and Zhang (2007) models shows a maximum deviation from the best fitting of 1.4 log unit and 0.94 log unit respectively for shoshonite and trachyte. As it can be noticed the model of Giordano et al. (2008) predict

higher viscosities than experimentally determined for shoshonite and latite composition (Figs. 3a and 3d), while the trachyte fitting is quite good (Fig. 3f). On the other hand the Hui and Zhang (2007) model show the maximum discrepancies for shoshonites at both low and high viscosity values (Fig. 3b), while at low viscosity for trachyte compositions (Fig. 3i).

5.2 The ascent rate of Campi Flegrei magmas

Geophysical precursors to volcanic eruptions, such as volcano-tectonic earthquakes, tremor and deformation, all reflect magma migration beneath the volcano as the magma develops an ascent path. A critical unknown that has limited the accuracy of eruption forecasting is the rate of magma rise before an explosive eruption: this parameter controls not only degassing behaviour and flow rheology, but also the timescale of accompanying precursory unrest and pre-eruptive warning. In this frame, viscosity data can be very useful because through them it is possible to estimate flow regime and magma rising velocity from deep to shallow reservoirs. Thus, experimental viscosity data allow us to semi-quantitatively estimate the ascent velocity of shoshonitic, latitic and trachytic magmas relevant to the Campi Flegrei caldera as outlined by Vetere et al. (2007). Assuming, for latite, shoshonite and trachyte, that magma ascent is driven by buoyancy, the overpressure ΔP at the depth at which these melts reside (Mangiacapra et al., 2008) may be estimated using the relation:

$$\Delta P = \Delta \rho g h \quad (5)$$

where $\Delta \rho$ is the difference between the density of the surrounding rock and the melt, g is the gravity, and h is the vertical length of the dike. $\Delta \rho$ is 200 kg/m³ for both shoshonitic and latitic melts. This value is the difference between 2500 kg/m³, which is the seismically average density of the crustal rocks and the density of the shoshonitic and latitic melts estimated at 1393 K and of the trachyte at 1218 K following Lange (1997) and Ochs and Lange (1999). We select 3.0 wt% as maximum water content because our data are well

constrained up to 3.0 wt%. Using equation (5) and the above selected parameters, we obtained an overpressure of 98 MPa. These values allow us to make a semi-quantitative estimate the Reynolds number Re within the dyke. It is well known that a laminar flow regime occurs at $Re < 10$, whereas a turbulent flow regime occurs $Re > 1000$. Transitional regimes are characterized by $10 < Re < 1000$. A critical value of the viscosity η_c between these regimes can be estimated, if ΔP , the width of the dyke w , and h are known, using the relation (Sparks et al., 2006):

$$\eta_c = [(2\Delta P \rho w^3) / (3h Re_c)]^{1/2} \quad (6)$$

where Re_c is the critical Re . Turbulent flow occurs when $\eta < \eta_c$. Here, we adopt the following values: $\Delta P = 98$ MPa (Eq. (5)), $\rho = 2500$ kg/m³, $h = 5$ km and $w = 2$ m. We chose these values according to Mangiacapra et al., (2008) and Zollo et al. (2008); we also select 10 and 1000 as representative values of Re_c .

Taking into account an initial temperature of the magmas of 1393 K for latite and shoshonite (Mangiacapra et al., 2008) and 1218 K for trachyte (Romano et al., 2003) and a water content of 3.0 wt % (Mangiacapra et al., 2008), a viscosity of 51 and 32 Pa s for shoshonite and latite respectively, and of 2691 Pa s for Agnano Monte Spina is calculated using Eq. (4). This effective value is lower than those estimated using Eq. (6) at $Re_c = 1000$ and 10 and $w = 2$ m.

From these data, we can conclude that the magma moved within the dike in a prevailing turbulent flow regime, at least between 9 and 4 km depth (Mangiacapra et al., 2008; Zollo et al., 2008; Vetere et al., 2011). To calculate the ascent speed u of such a magma we use the relation of Lister and Kerr (1991) for turbulent flows:

$$u = 7.7 [w^5 / \{\eta (\rho g \Delta \rho)^3\}]^{1/7} g \Delta \rho \quad (7)$$

by setting $w = 2$ m, $\Delta \rho = 200$ kg/m³ and η (hydrous) of latite, shoshonite, and trachyte, respectively. By selecting u , the ascent time (h/u) for shoshonite magma between 9 and 4 km

of depth is in the order of 4.4 min; while for latite is 4.1 min and for Agnano Monte Spina is 7.6 min.

The ascent velocity determined for a 2 m wide dike is (a) the same comparing AMS and alkali basalt (Demouchy et al., 2006); (b) similar to that estimated for kimberlites (from 1 to 40 m/s; Peslier et al., 2008).

Our simple model (Eqs. (6) and (7)) does not consider the possible role of : 1) freezing processes at the walls, which can locally increase the viscosity (Wylie et al., 1999); 2) the variation of the dike geometry in depth (Giberti and Wilson, 1990); 3) possible vesiculation processes, which can further decrease the magma viscosity (Manga and Lowenberg, 2001). Therefore, our velocity estimates must be considered as representative of “order of magnitude” rather than absolute values.

5. Conclusion

We determined the viscosity of dry and hydrous latite and shoshonite compositions representative of Campi Flegrei relatively primitive magmas at temperatures relevant to magmatic processes. We provide a modified VFT equation to calculate viscosity as a function of temperature and water content in the values range as investigated in this work; we have demonstrated that the same equation can be used to calculate viscosity of compositions representative of more evolved magmas as well (i.e. trachyte).

Viscosity data as determined from the equation provided in this study can be used to constrain the ascent velocity within dikes and used for hazard assessment at the Campi Flegrei area. Using petrological data and volcanological information, we estimate the time scale for the ascent of magmas from 9 km to 4 km depth (where deep and shallow reservoirs, respectively, are located) in the order of few minutes.

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Fig. 1. Structural sketch of the Campi Flegrei caldera (after Orsi et al., 2004) showing the location of shoshonite (Minopoli) and latite (Fondo Riccio) vents.

Fig. 2. Low and high temperature viscosity data for dry and hydrous a) shoshonitic and b) latitic compositions. Lines are predictions by Eq. (4). Low temperature data are measured at atmospheric pressure. High temperature data for shoshonite and latite were obtained at atmospheric pressure and at 0.5 GPa. Gray symbols are data from piston cylinder.

Fig. 3. Comparison between experimental viscosity data and the predictions of computation models. a) shoshonite, this work model; b) shoshonite, Hui and Zhang (2007); c) shoshonite, Giordano et al. (2008); d) latite, this work model; e) latite, Hui and Zhang (2007); f) latite, Giordano et al. (2008) g, h, i) trachyte vs Giordano, Hui and Zhang and this work model respectively melts.

Fig. 4. Comparison among ascent rate estimates for trachyte (Agnano Monte Spina), latite (Fondo Riccio), shoshonite (Minopoli), and other types of magma. Overall, ascent rates for kimberlites are higher than those for alkali basalts and other magma types and are of the same order of magnitude when compared with our compositions. **Kimberlite:** H diffusivity in olivine combined with the equilibration depth of xenoliths in kimberlites (Peslier et al., 2008); **Stromboli basalt:** (Misiti et al., 2009); **FR, MIN and AMS:** this work; **Alkali Basalt:** H in olivine from garnet–peridotite xenolith in alkali basalts (Demouchy et al., 2006); **Andesite Dacite:** Mt St Helens: groundmass crystallization, hornblende rims, mass-eruption rates, seismicity movement (Rutherford and Gardner, 2000).

Table 1. Electron microprobe analyses and water content of starting materials used for viscosity measurements; FR refers to latitic composition from Fondo Riccio, MIN refers to shoshonitic composition from Minopoli. After experiments water contents were measured on selected runs only (those carried out at the highest experimental temperature).

	FRd_1	FRh_2	FRh_4	MINad_1	MINah_2	MINah_1
SiO ₂ (wt%)	56.08	53.13	53.30	52.86	51.07	49.92
TiO ₂	0.89	0.86	0.84	0.84	0.85	0.83
Al ₂ O ₃	18.83	17.29	17.91	16.27	15.97	15.29
FeO _{tot}	6.57	6.22	6.63	7.00	5.51	6.98
MnO	0.13	0.16	0.17	0.13	0.12	0.09
MgO	2.48	2.44	2.35	5.66	5.63	5.36
CaO	5.87	5.38	5.67	10.29	10.01	9.63
Na ₂ O	4.21	4.08	4.06	2.28	2.26	2.12
K ₂ O	4.67	4.74	4.49	3.79	3.77	3.62
P ₂ O ₅	0.64	0.63	0.62	0.42	0.43	0.44
Total	100.32	94.94	96.04	99.54	95.61	94.29
H ₂ O (KFT) ^{be}	n.d.	2.84	3.28	n.d.	2.35	3.30
H ₂ O (FTIR) ^{be}	n.d.	3.11	3.40	n.d.	2.58	3.85
H ₂ O (KFT) ^{ae}	n.d.	2.10 ²⁾	3.24 ³⁾	n.d.	2.12 ⁵⁾	3.10 ⁶⁾
H ₂ O (FTIR) ^{ae}	0.22 ¹⁾	3.65 ²⁾	3.39 ³⁾	0.19 ⁴⁾	2.42 ⁵⁾	3.46 ⁶⁾

H₂O contents were measured by Karl Fischer Titration (KFT) and Fourier Transform Infra-Red (FTIR) at University of Hannover; FTIR data are MIR for runs ¹⁾ and ⁴⁾, NIR for all other runs. be: before experiments; ae: after experiments: ¹⁾ FRd_1_1; ²⁾ FRh_2_3; ³⁾ FRh_4_3; ⁴⁾ MINad_1_1; ⁵⁾ MINah_2_3; ⁶⁾ MINah_1_3; see Table 3 for run labels.

Table 2. Viscosity data of latitic (FR) and shoshonitic (MIN) compositions obtained by means of concentric cylinder and micropenetration methods. The error in the viscosity measurements is ± 0.05 log unit.

T (K)	H ₂ O (wt%)	FR	MIN
		log η (Pa s)	log η (Pa s)
High temperature viscosities, concentric cylinder method			
1866	0.01	1.02	0.44
1842	0.01	1.08	
1818	0.01	1.18	0.52
1792	0.01	1.29	0.61
1770	0.01	1.39	0.70
1745	0.01	1.50	0.89
1718	0.01	1.61	0.99
1695	0.01	1.72	1.07
1669	0.01	1.85	1.19
1645	0.01	1.97	1.31
1621	0.01	2.10	1.43
1597	0.01	2.24	1.56
1572	0.01	2.37	1.69
1548	0.01	2.52	1.84
1522	0.01	2.66	1.98
1497	0.01	2.83	2.14
1473	0.01	2.99	2.31
1449	0.01	3.16	2.49
1425	0.01	3.35	2.68
1399	0.01		2.88
Low temperature viscosities, micropenetration method			
1044	0.01	10.10	
1027	0.01	10.43	9.00
1022	0.01	10.52	
1014	0.01	10.62	
1008	0.01	10.73	9.72
991	0.01		9.95
987	0.01	11.05	
971	0.01	11.32	
957	0.01		11.20
955	0.01		11.30
952	0.30	9.40	
943	0.30	9.60	
935	0.30	9.41	
931	0.30	10.10	
929	0.30	10.16	
928	0.50	9.66	
918	0.50		8.00
910	0.50	10.50	
901	0.50	10.80	
886	0.50		10.12
879	0.50		10.77
915	0.80	10.03	
910	0.80	10.25	
907	0.80	10.35	
882	1.00		9.08
909	1.20	10.10	
847	2.43		9.00
845	2.43		9.39
842	2.43		9.68

Table 3. Experimental conditions and viscosity values obtained by means of falling sphere method.

Sample	Run number	H ₂ O (wt%)	T (K)	Sphere radius ^{a)} (μm)	t _{ef} ^{b)} (s)	d ^{c)} (mm)	Log η (Pa·s)
MINad_1_1	PC-510	0.01	1523	120	1800±19	5.04	2.32±0.15
MINad_1_2	PC-505	0.01	1573	70	1800±19	4.69	1.88±0.15
MINad_1_3	PC-506	0.01	1623	90	600±20	5.16	1.58±0.15
MINad_1_4	PC-508	0.01	1673	65	300±21	6.01	0.93±0.16
FRd_1_1	PC-510	0.01	1523	215	1800±24	5.49	2.79±0.15
FRd_1_2	PC-505	0.01	1573	145	1800±25	6.10	2.40±0.15
FRd_1_3	PC-506	0.01	1623	180	600±26	4.62	2.23±0.15
FRd_1_4	PC-508	0.01	1673	160	300±27	5.14	1.78±0.17
MINah_2_1	PC-528	2.35	1423	105	900±17	4.56	1.72±0.15
MINah_2_2	PC-514	2.35	1473	115	300±18	6.37	1.40±0.16
MINah_2_5	PC-540	2.35	1473	115	300±18	4.68	1.77±0.16
MINah_2_3	PC-515	2.35	1523	75	300±19	6.36	1.03±0.16
MINah_2_4	PC-530	2.35	1523	75	300±19	6.45	0.72±0.16
FRh_2_1	PC-528	2.84	1423	60	900±21	4.75	1.14±0.15
FRh_2_2	PC-514	2.84	1473	75	300±22	5.41	1.10±0.16
FRh_2_5	PC-540	2.84	1473	75	300±22	6.83	1.00±0.16
FRh_2_3	PC-515	2.84	1523	50	300±24	6.77	0.65±0.16
FRh_2_4	PC-530	2.84	1523	50	300±24	6.85	0.35±0.16
MINah_1_1	PC-503	3.30	1423	105	300±17	3.89	1.53±0.16
MINah_1_2	PC-516	3.30	1473	90	300±17	5.52	1.25±0.16
MINah_1_3	PC-517	3.30	1523	75	300±19	6.96	0.99±0.16
MINah_1_4	PC-529	3.30	1523	75	300±19	6.88	0.69±0.16
FRh_4_1	PC-503	3.28	1423	90	300±21	5.21	1.27±0.16
FRh_4_2	PC-516	3.28	1473	55	300±22	7.14	0.71±0.16
FRh_4_3	PC-517	3.28	1523	50	300±24	6.32	0.68±0.16
FRh_4_4	PC-529	3.28	1523	50	300±24	6.12	0.39±0.16

H₂O (wt%) refers to the initial water content. The error in the temperature measurement is around 10 K.

^{a)} The radii of hand-picked spheres were measured using a microscope calibrated with a micrometer section (see Vetere et al., 2006). The error in the measurements is of comprise between 1 and 5 μm.

^{b)} Effective run duration. See text.

^{c)} Falling distance of the sphere. The error in the measurement of falling distance is about 10 μm (see text).

Table 4. VTF parameters for viscosity equations. Numbers in parenthesis are standard deviation.

Parameters	Latite FR	Shoshonite MIN	Trachyte AMS
a	4.9918 (± 0.3129)	5.5658 (± 0.332)	6.64 (± 0.7357)
b	5412.9881 (± 368.5425)	7812.0455 (± 596.324)	8464.73 (± 1332.511)
c	552.689 (± 15.9128)	321.7306 (± 29.5606)	186.36 (± 56.9934)
d	2799.217 (± 263.4522)	874.6774 (± 46.6082)	7220.89 (± 961.4282)
e	303.4056 (± 75.3107)	770.0389 (± 11.3649)	-129.20 (± 149.674)
g	-5356.4401 (± 473.0276)	-2289.7318 (± 91.9453)	-429.34 (27.556)

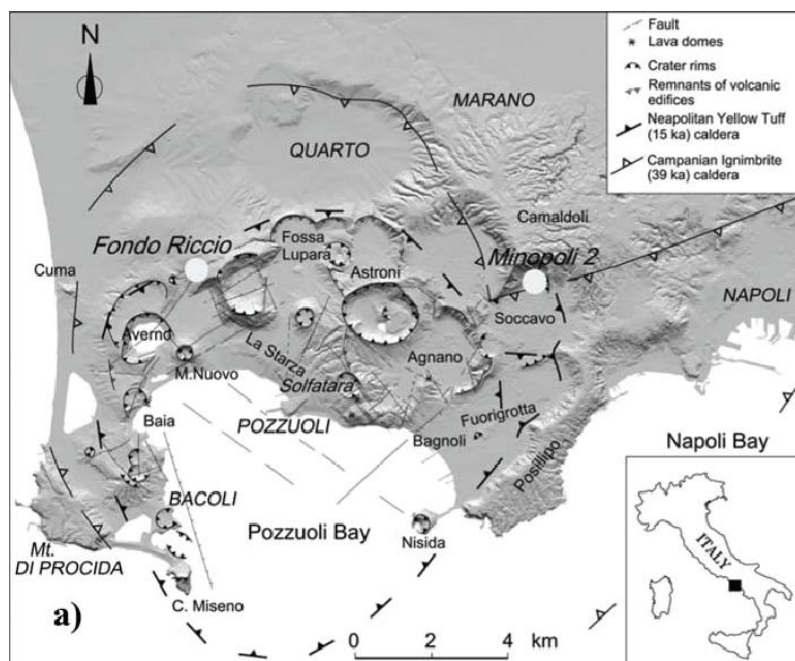


Figure 1

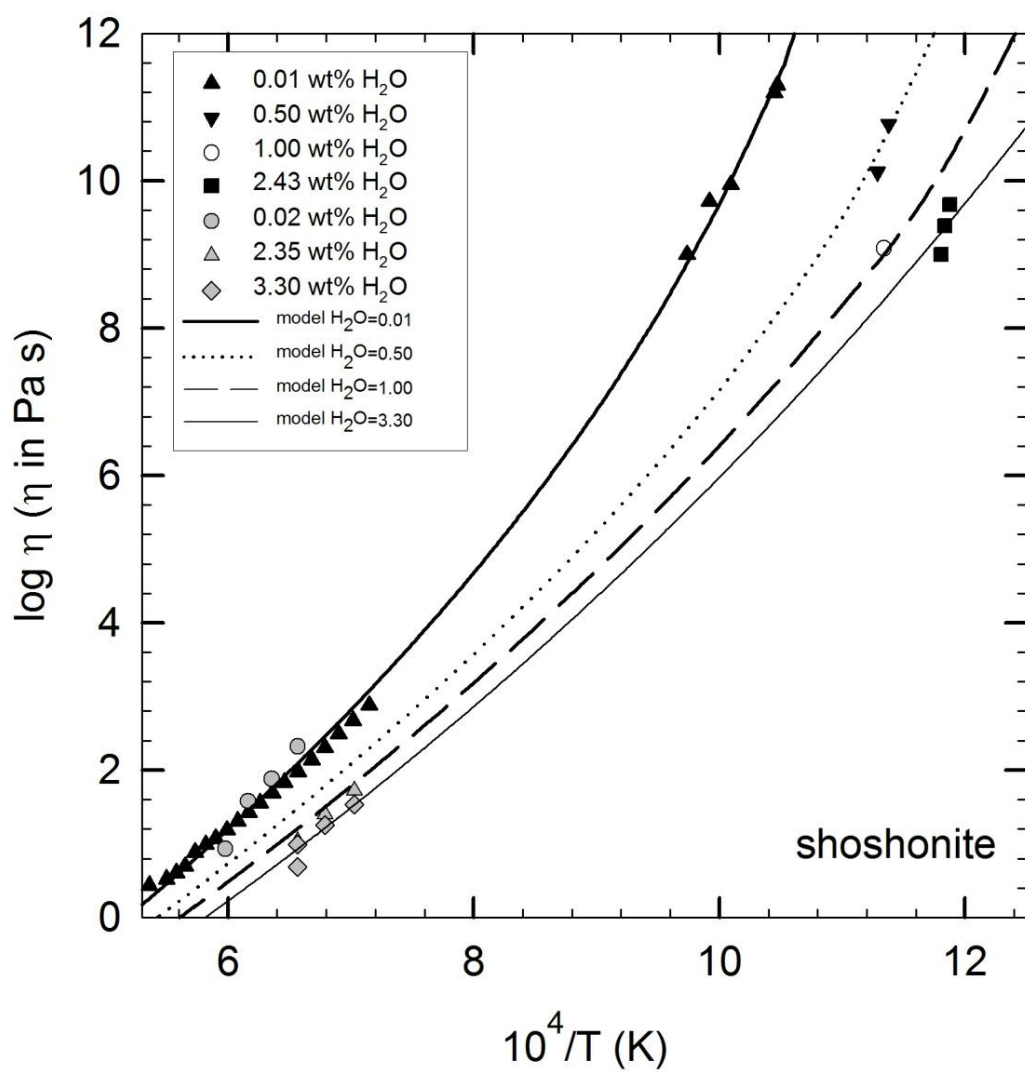


Fig. 2a

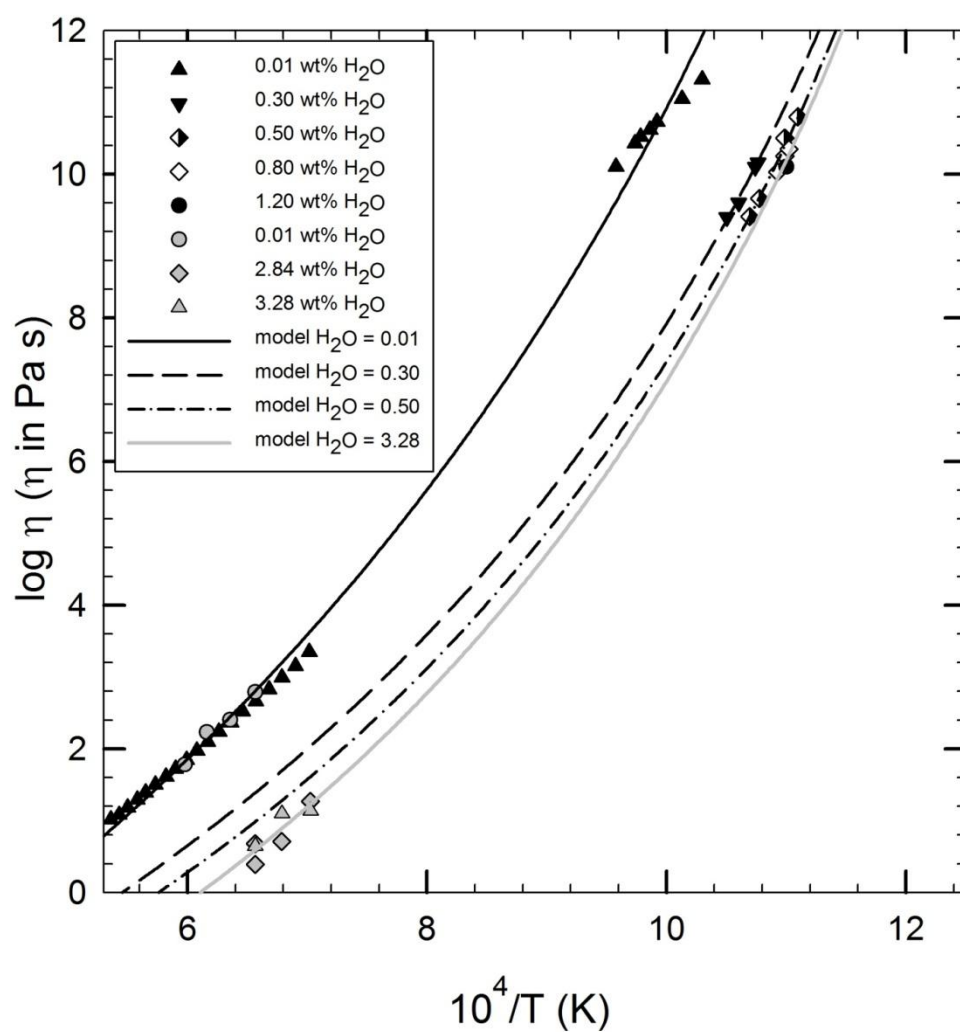


Fig. 2b

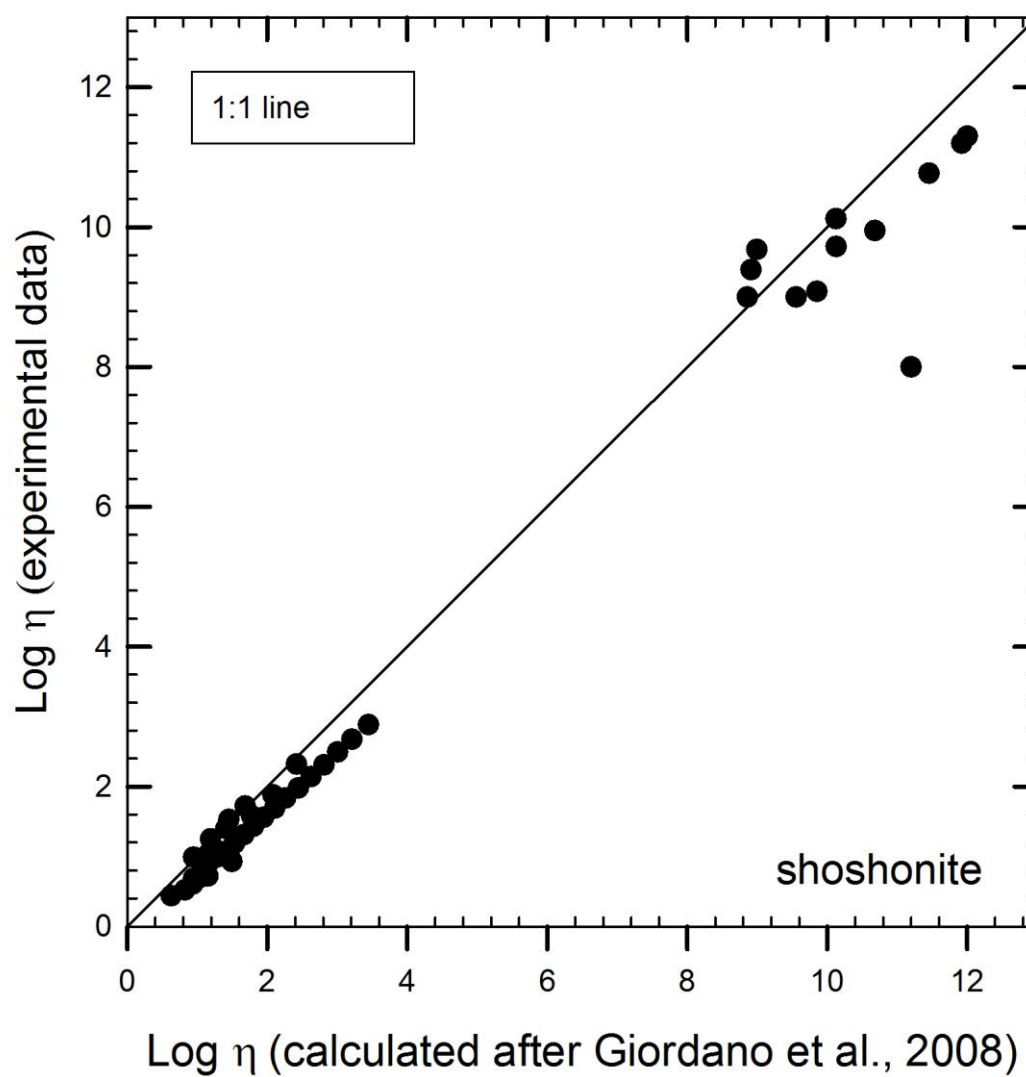
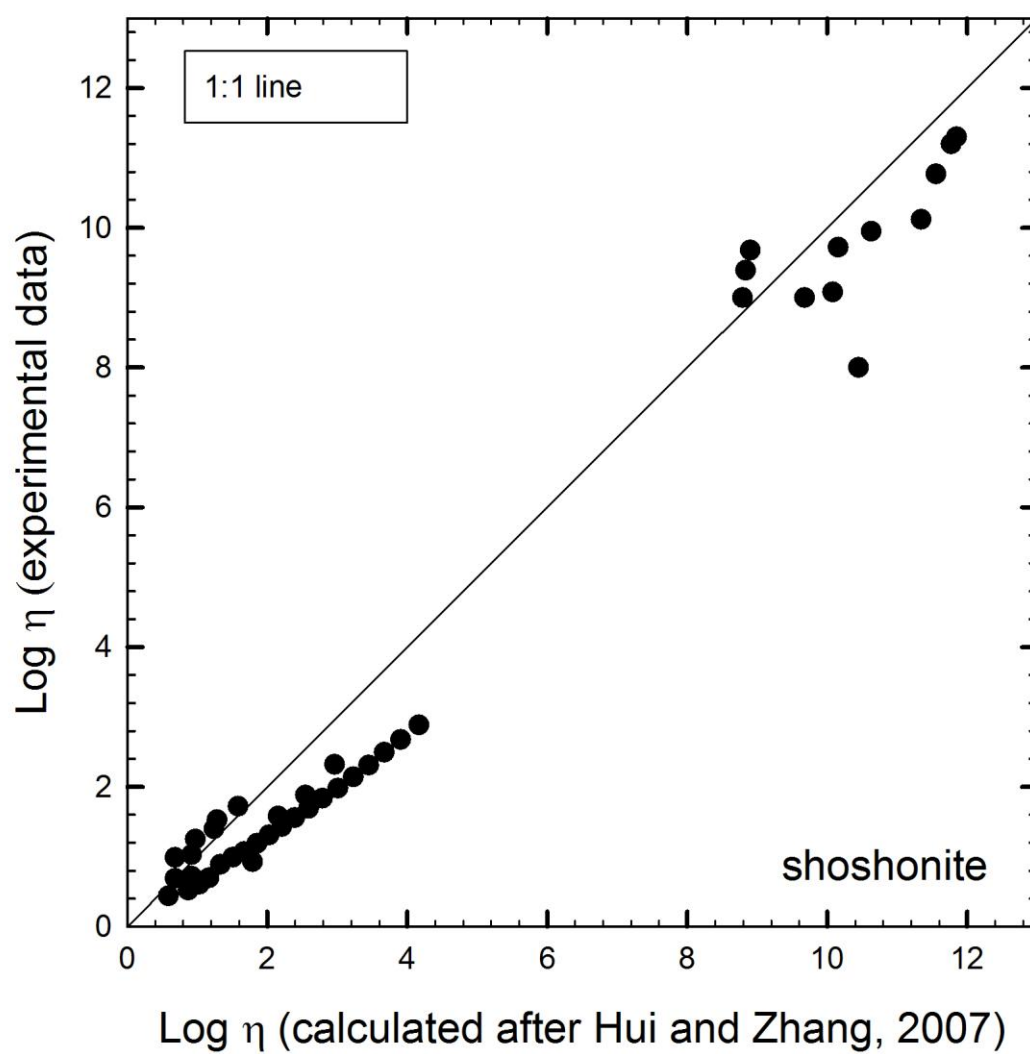


Figure 3a

**Figure 3b**

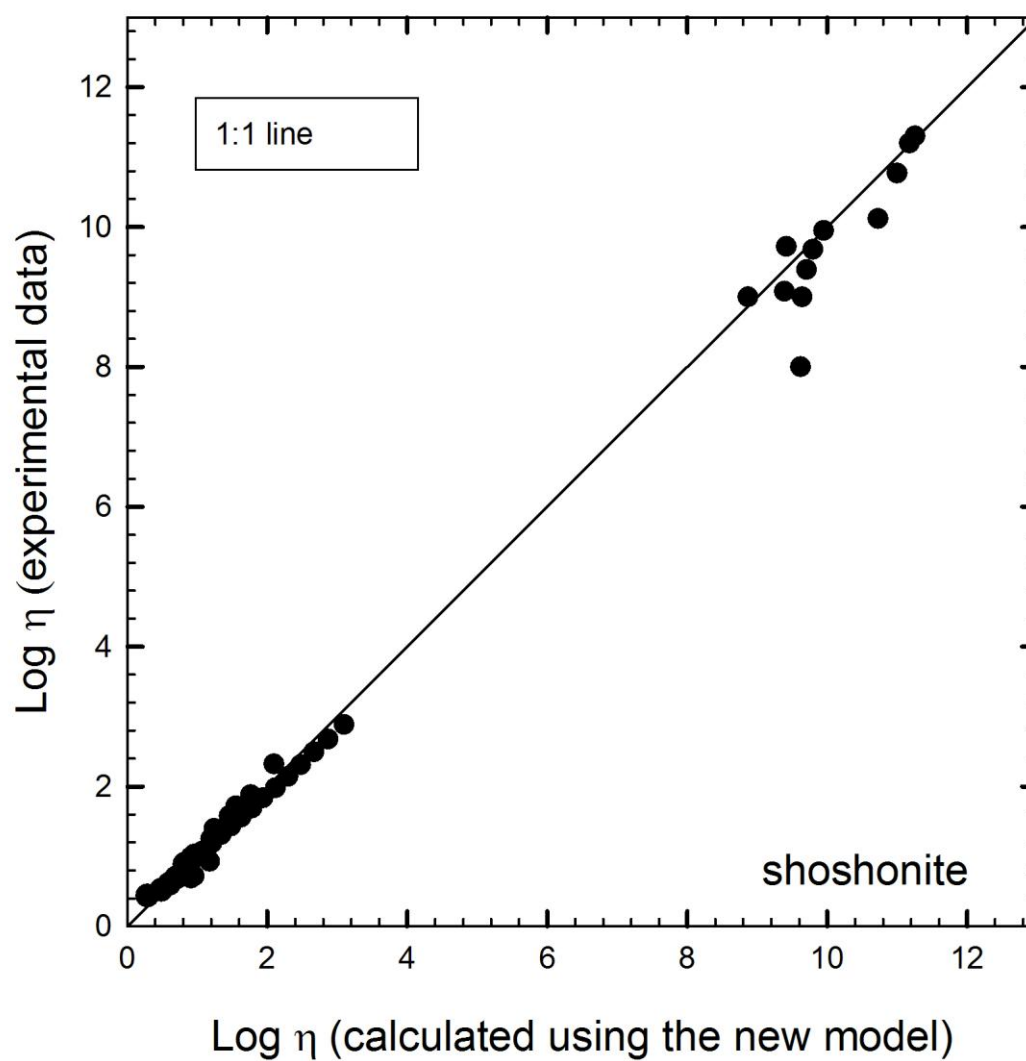


Figure 3c

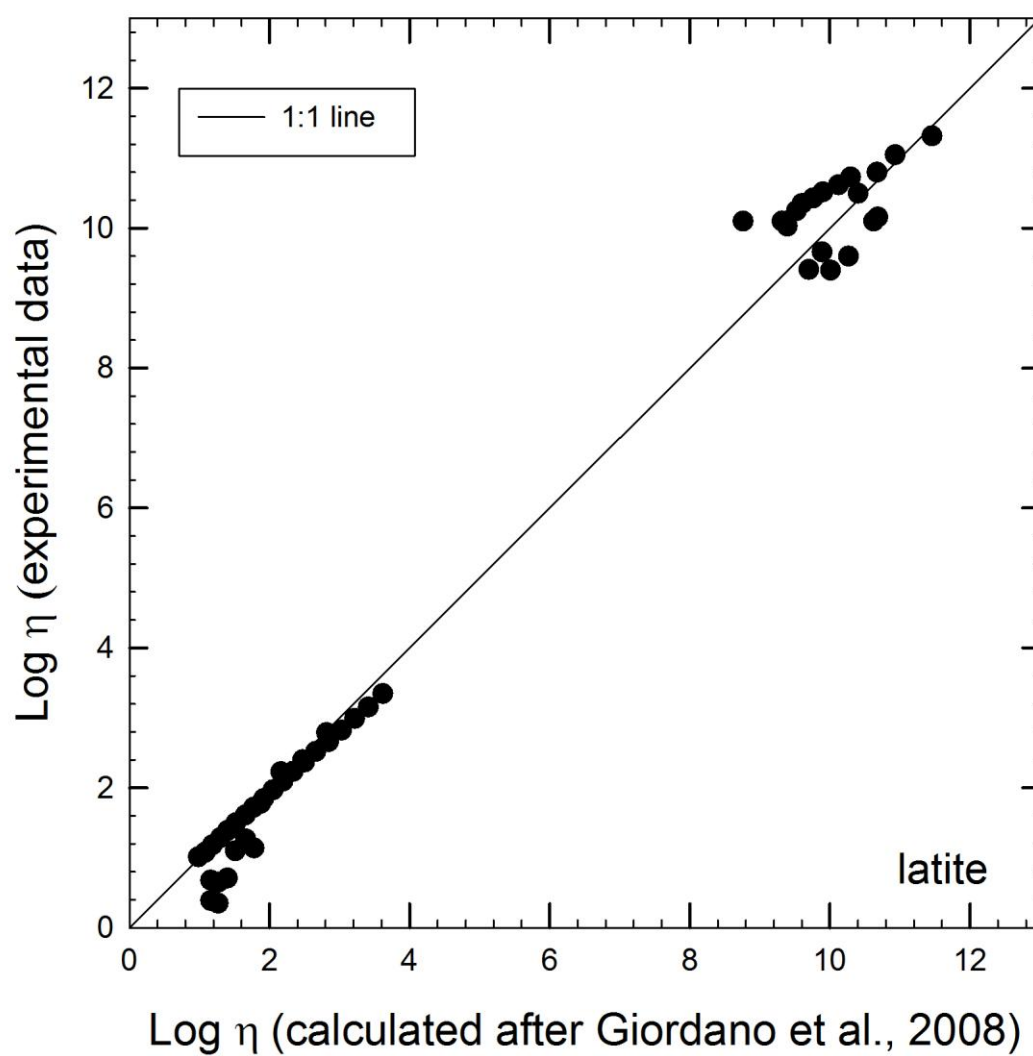
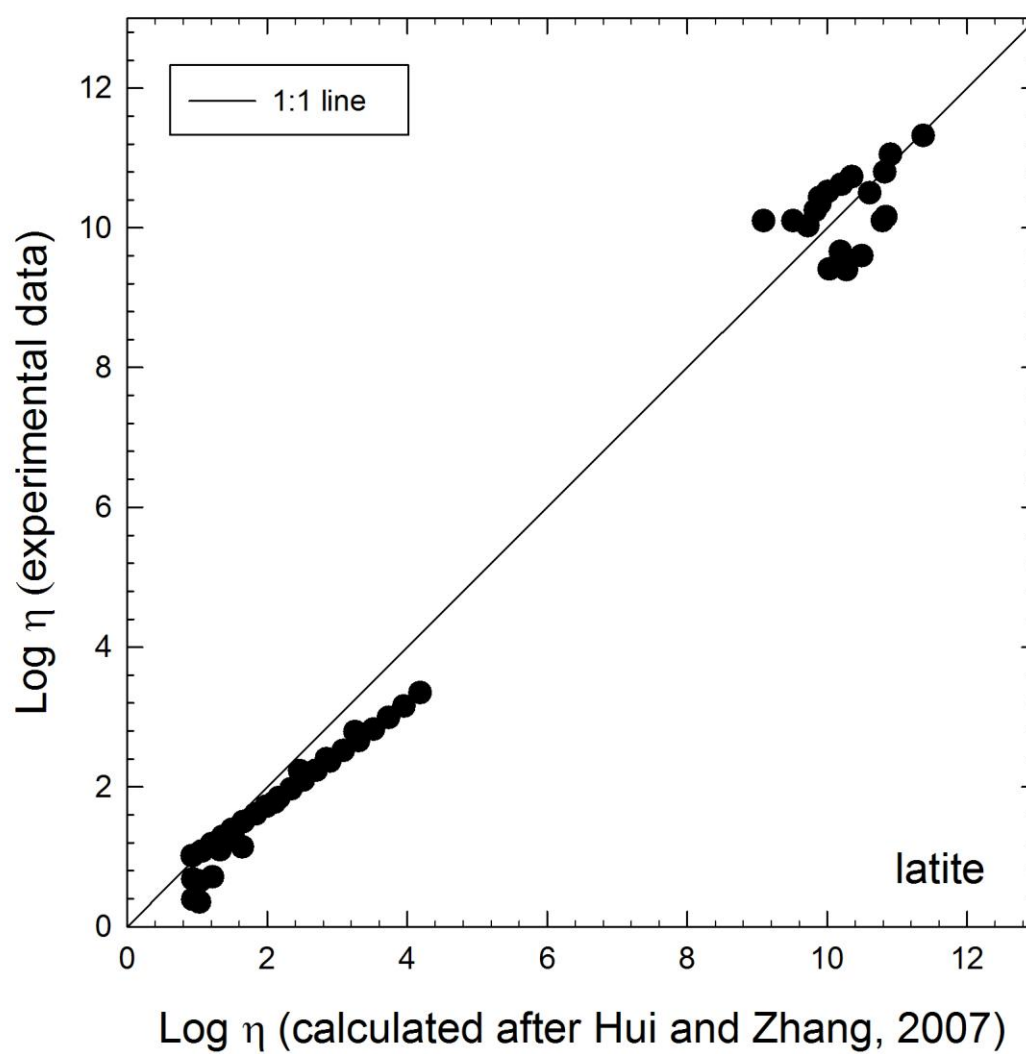


Figure 3d

**Figure 3e**

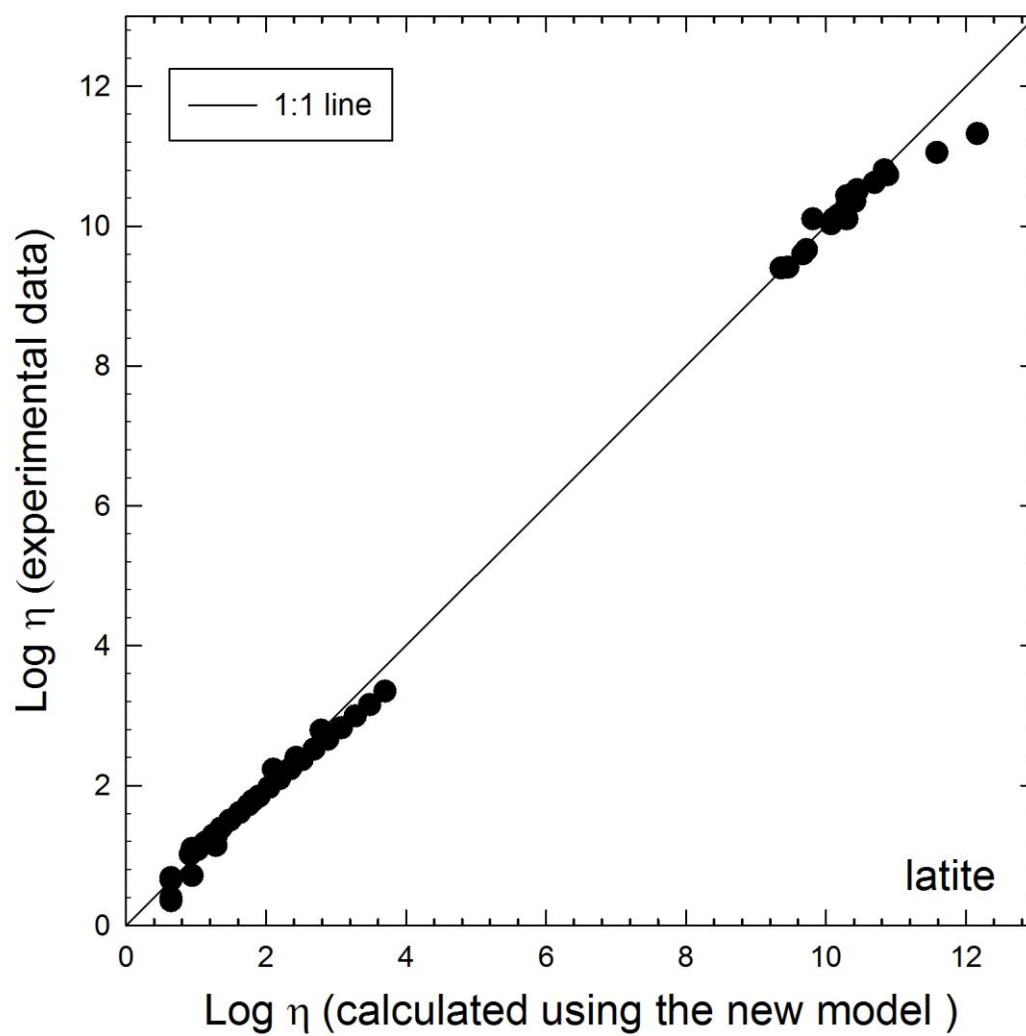


Figure 3f

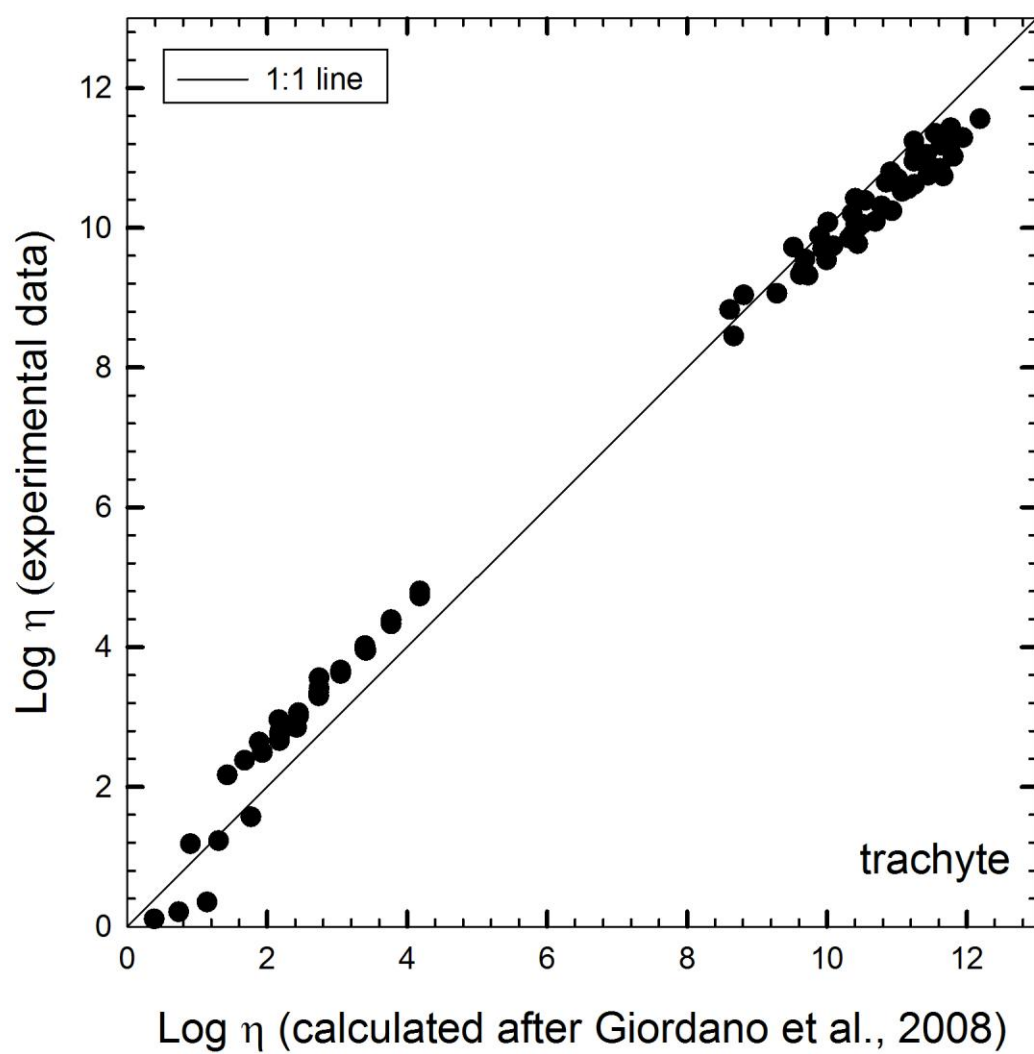
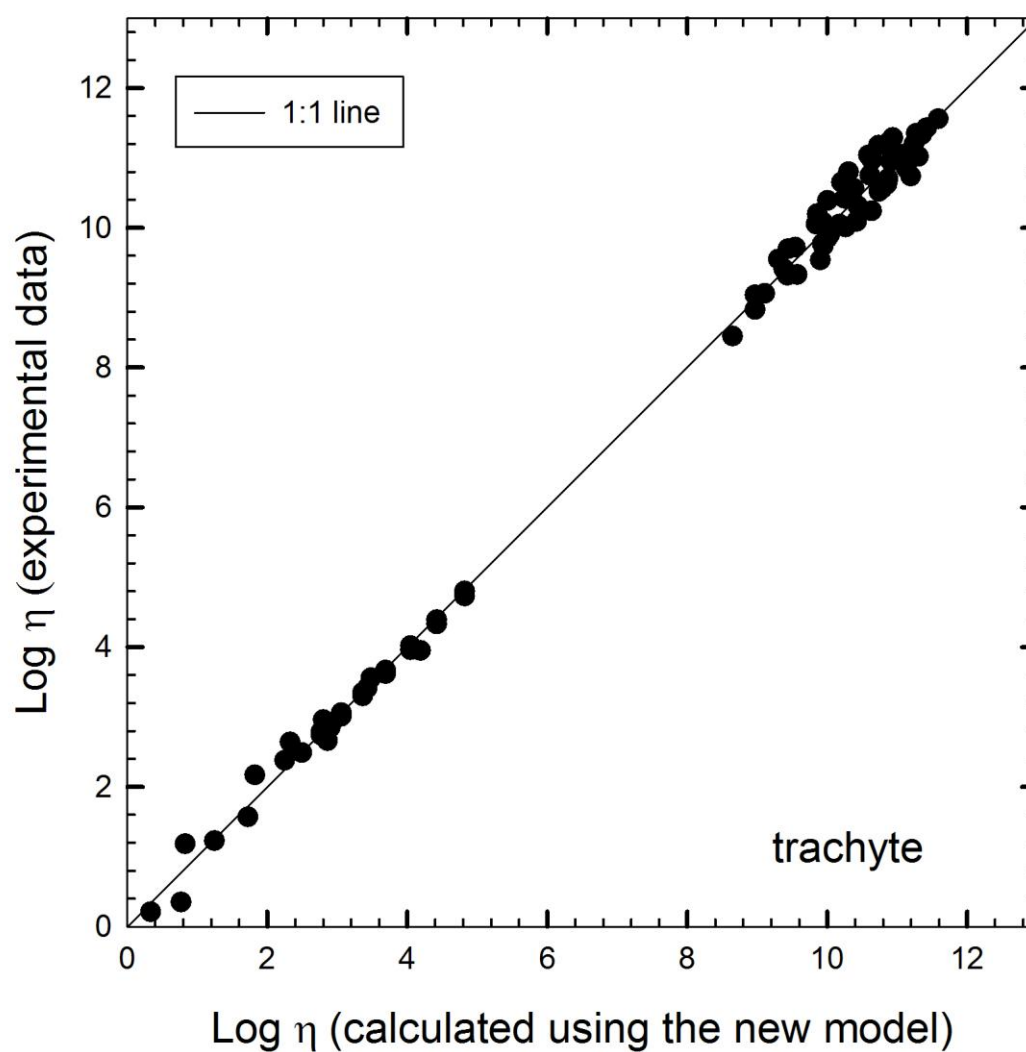
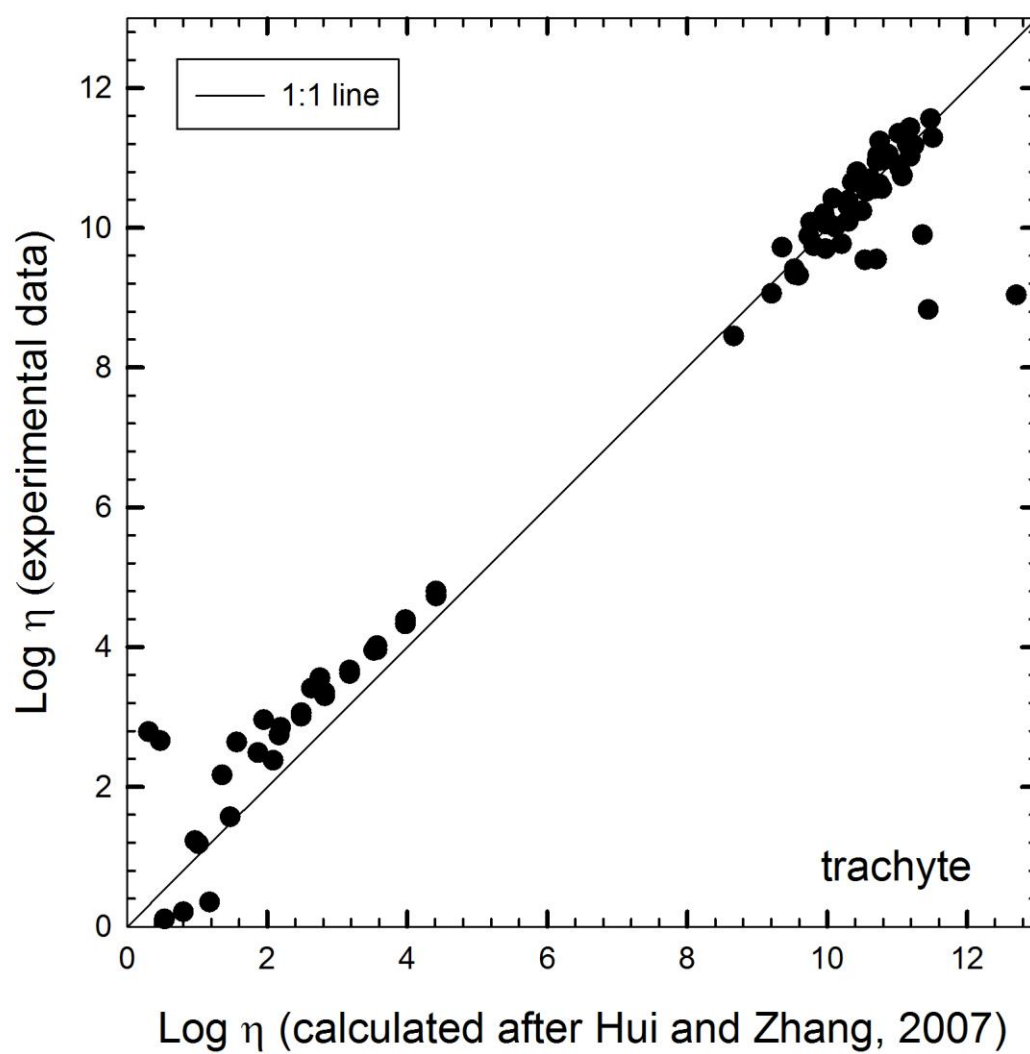


Figure 3g

**Figure 3h**

**Figure 3i**

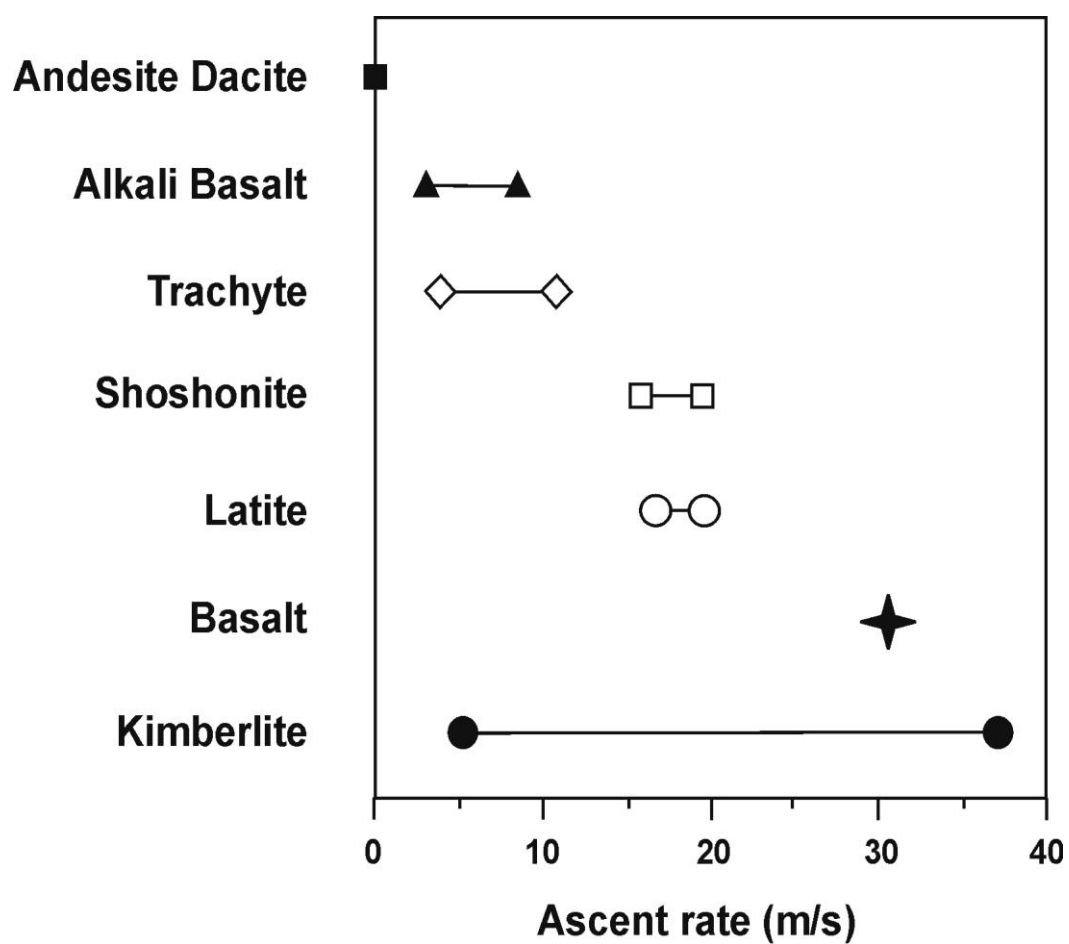


Figure 4

Highlights

- 1) We experimentally measured viscosities of shoshonitic and latitic melts relevant to the Campi Flegrei caldera magmas.
- 2) The micropenetration, concentric cylinder technique and falling sphere method were adopted to determine viscosity of nominally anhydrous and hydrous melts.
- 3) The combination of experimental data allowed us create a general model of viscosity using the modified VFT equation.
- 4) The proposed model has been applied to Campi Flegrei products.
- 5) Viscosity data have been used to constrain the ascent velocity of melts within dikes.